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THE APPLICATION OF DAYLIGHTING RESEARCH TOOLS TO FENESTRATION AND BUILDING DESIGN OPTIMIZATION

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Summary

It is commonplace in both the building research and design communities to separate the two endeavors and accentuate the differences between them. We often hear that the researchers' tools and approaches are not useful for design purposes; they are too slow, and too complex, and while they generate quantities of data, they provide little useful information. While this will often be true, there are significant cases where it is not so. By exploring these in more detail we can learn more about the complementary nature of research and design.

Background

Neither research nor design is a simple, singular event or process. Each is a rich and complex set of procedures that has its own internal structure, its own activities, and its own traditions. The researcher utilizes an array of analytical and experimental tools; the designer uses an equally large array of "design tools." The problem we hear of most often occurs when a designer tries to use an inappropriate research tool for design purposes. It can also be equally frustrating and disastrous to use a design tool for design purposes for which it was not intended. Another common belief is that researchers generate much data but little useful information. Both these comments reflect differences in perspective, style, goals, and needs, rather than irrevocable differences between researchers and designers. Furthermore, in an increasingly complex world there is continuous pressure in the design field to force building designers to address more complex performance issues and interrelated problems in the built environment. This will inevitably require more sophisticated design tools and techniques to extract and manipulate useful design information from data obtained from many sources. Some of these tools and techniques might readily be adapted from existing or proposed research tools. We believe that the increasingly difficult task of optimizing building design to meet occupant, client, and societal needs can be facilitated by a better understanding of building sci-ence research directions and the application of selected building research tools, with appropriate modifications, for design purposes.

Similarities and Differences: Research and Design

It is instructive to note that the similarities between the design process and the research process are sometimes stronger than the differences. The essence of architectural design is problem-solving; research into the client's needs, into the environmental, sociological, and economic context that limits viable solutions; development of alternative solutions; testing of these solutions against the design program; and finally, through an iterative process of increasing detail, a synthesis of all the competing issues and elements into a final design. Within the context of a specific design solution, there may be more or less leeway for artistic creativity and visual expression. In some cases, artistry conflicts with technical solutions; in other cases, clever designers may evolve striking imagery from technical requirements. But the basic process of problem statement, identification and evaluation of alternative solutions, and iterative testing and modification of those solutions is common not only to design but to research as well.

One of the key requirements for good design and good research is a careful definition of the problem. This is essential if the potential of alternative proposed solutions is to be adequately tested. Some tools can help generate alternative solutions, and others can help test the adequacy of solutions. "Synthesis" tools often require a healthy dose of experience, intuition, insight, and in some cases, just plain luck to arrive at good solutions. "Analysis" tools are generally applied through more routine procedures with less room for individualized contributions. On the other hand, analysis tools (e.g., microcomputer models) are often called upon to analyze problems for which they were never designed; in this context they require the guidance of expert users to produce meaningful and useful results. In some cases the same tool can be used for analysis or

synthesis, depending on the available information and the skill of the user. If a tool is used to test the validity of a single solution, the limited analytical result provides very limited information (e.g., confirms that a design meets a minimum code requirement). However, if the same tool is used to analyze a carefully constructed parametric set of alternatives or options, analysis of that set of results may provide the kind of critical information useful in generating or synthesizing new design solutions.

Another important difference between research tools and design tools is the context in which they are used. A designer faced with a tight budget, a critical deadline, and a client having strong opinions will have one perspective on the problem-solving process and the use of tools in that process. A researcher, however, normally has a different type of client, may have more time in which to develop solutions, but may also have other constraints, e.g., "publish or perish" and a tight budget. Frequently, the researcher's perspective will be somewhat more generic than that of most designers, who are commissioned to design specific buildings. However, even these differences between designers and researchers lie within the very broad spectrum of project experience that many design firms have had. We conclude, therefore, that there are no fundamental or irrevocable barriers that prohibit useful interchanges between these groups. In fact, in the following sections we argue that each group will benefit if the other reviews, utilizes, and critiques the work of the other.

Fenestration Design/Research Tools

To move this discussion from the general to the specific, we consider the problems of optimizing fenestration design in commercial buildings, where the building envelope must address thermal and daylighting concerns. The Window and Daylighting Group in the Energy Efficient Buildings Program at Lawrence Berkeley Laboratory (LBL) conducts research to develop the technical basis for better understanding and utilizing fenestration systems (windows, skylights, atria, etc.) cost-effectively to reduce energy requirements in buildings while maintaining or improving health, comfort, and productivity. A multidisciplinary team of architects, engineers, physicists, and others at LBL, with assistance from consultants and subcontractors, has been working in this field since 1976.

If daylighting strategies are to positively influence the new generation of energy-efficient buildings, we need to answer three simple but critical questions: 1) what works? 2) how well does it work? 3) why does it work? The last ques-

tion is important because some successful designs may work for the "wrong" reasons. Unlike some building systems, daylighting strategies are not hidden within the fabric of the building but are exposed for all to see. Design failures, such as visual discomfort due to glare conditions, are often obvious and the subject of bitter occupant complaints. Success, as measured by occupant response to esthetics, view, and the overall quality of the indoor environment, may be equally obvious and pleasing. The energy impacts, however, are often less obvious and generally require a significant technical effort to quantify. Understanding the impact of daylighting on energy issues may be complicated by the fact that the essential elements of good lighting design are a mystery to many architects and engineers.

Daylighting's potential benefits can be easily enumerated. It can 1) enhance the quality of the indoor luminous environment, 2) improve visual performance, 3) reduce electric lighting energy consumption, 4) reduce heating and cooling loads, 5) reduce HVAC system size, and 6) reduce peak electrical demand. However, not all daylighting strategies will necessarily achieve all six goals; in some circumstances some benefits can only be achieved at the cost of reducing others. To properly evaluate the successes and failures of a particular design, it is necessary to establish clearly defined goals and objectives that explicitly address the issues mentioned above. Ideally, comparing what was achieved in a design to what was intended will provide feedback to assist with subsequent building designs. As architectural designs become more sophisticated, the tools to develop and evaluate them must correspondingly increase in predictive power.

One reason for clearly distinguishing which design decisions apply to lighting quality, lighting energy consumption, peak demand impact, etc., is that the design and evaluation tools may be quite different for each. Furthermore, the requirement for design tools that will enable adequate analysis or evaluation of each of these issues will vary depending on when in the design process they are used. As one moves through the design process and then through construction and occupancy, one's concerns and perspective changes, and the quality and quantity of information required change significantly. Failure to recognize this often results in applying an inappropriate design tool that may produce incorrect or misleading results even if it is properly applied. Worse yet, when appropriate design tools are not available, one may tend to let the design tool output dictate design direction. This reinforces the saying that when one's only tool is a hammer, every problem looks like a nail.

Application of Research to Design

To illustrate the preceeding assessment, we will discuss, in more detail, new directions in daylighting research that may have immediate or longer term spinoff and application for designers. We divide the discussion into three areas: 1) tools and models to predict illuminance distribution, 2) techniques to better understand the lighting quality implications of daylighted buildings, and 3) energy analysis tools. These are meant to illustrate the points made earlier and are drawn primarily from ongoing research activities at Lawrence Berkeley Laboratory. However, we believe the comments are also generally applicable to research in other areas of building science conducted by other groups.

Illuminance Prediction Tools

The ability to predict illuminance distribution patterns in daylighted spaces is essential if we are to design to meet visual performance needs. We frequently classify these techniques based on presentation format: nomographs, protractors, computer models, etc. However, a more important distinction is the source of the data used in the design tool. Data originally derived from model measurements have different limitations than do data derived directly from a mathematical simulation. It is currently fashionable to talk about "user-friendly microcomputer programs," and it is clear that as their computational power and their "friendliness" increases, these may become the tool of choice for many designers. However, most computer models have buried within them a vast number of assumptions and approximations; it can be dangerous to use these tools in situations where their limitations are stretched or violated. These tools are relatively cheap and can be very fast. When one desires more accuracy, one generally requires more computational complexity, therefore sacrificing speed. We often find that modeling accuracy and speed are inversely related.

An alternative approach, the use of photometric data measured in scale models, can provide good data for quantitative and qualitative investigations. However, this approach has fundamental limitations as well as practical constraints. The quality and accuracy of the measurements is limited by the skill and knowledge of the team conducting the measurements as well as by the capabilities of the photometric instrumentation (which can represent a sizable investment for most firms). The level of detail required to produce high-quality measurements will normally require that significant time be invested in model building and testing. Furthermore, testing under outdoor skies introduces unpredictable, non-repeatable events that complicate the data analysis. Finally, we note that the most sophis-

ticated design solutions developed to meet the most critical visual performance and visual comfort needs are often exactly those that are difficult to model using commonly available design tools.

To better understand the impact of architectural design decisions on interior illuminance distribution, we have developed a series of computational and scale-modeling research vools that enable us to determine the effects of key design variables on illuminance distribution. While the operating constraints for daylighting research are not identical to those for design, they share some attributes. For example, the researcher using a complex computer model would rather not have to write a new computer model each time a different architectural design is to be analyzed. From the perspective of scale modeling, it is not cost-effective for either the designer or the researcher to build dozens and dozens of detailed scale models that include all of the design features of interest in all of their combinations.

To solve the scale model measurement problem, we designed and constructed a large hemispherical sky simulator for model testing. This facility, shown in Figure 1, measures 24 feet in diameter and will accommodate relatively large models.
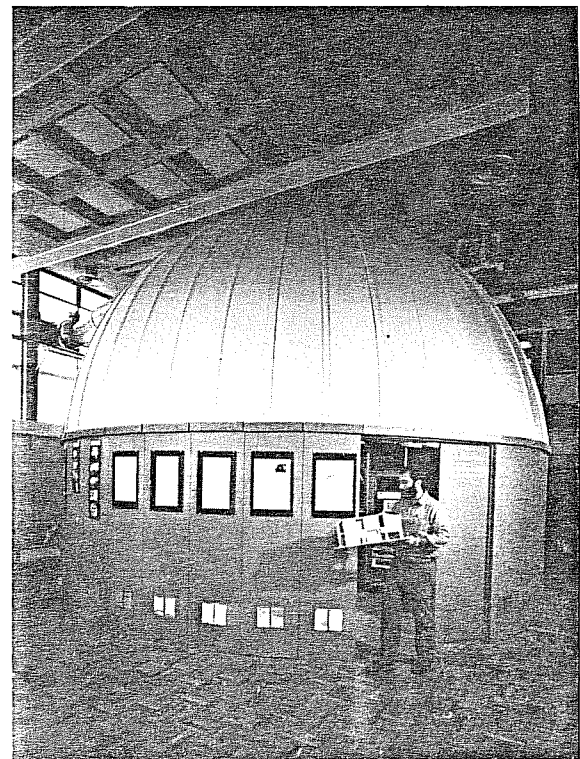

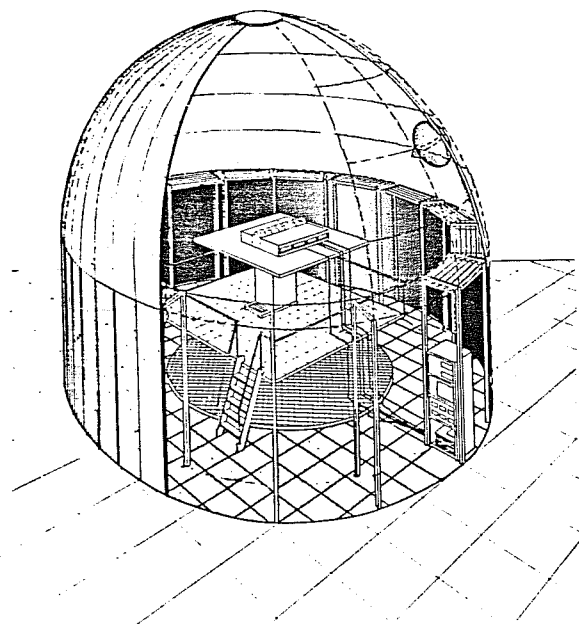Figure 1.A: Photograph of sky simulator.

Figure 1.B: Schematic of sky simulator.

A computer-controlled lighting system pro-
vides a variety of standard and non-standard sky
luminance distributions on the inner surface of
the dome. A sun simulator can be positioned at
any solar incidence angle and provides a col-
limated beam to simulate direct sun impacts. A
ground-reflected component of daylight can be
simulated separately from the sun and sky com-
ponents. A computerized data-acquisition system
collects data from up to 80 photometric sensors
placed throughout the models being tested. This
facility is used to collect illuminance distribu-
tion data for a variety of room configurations and
fenestration systems under a range of standard sky
conditions.

The use of sky simulators to create reprodu-
cible building exterior luminous environments for
a systematic series of model tests is not a new
concept. However, incorporating the features
described above into a single test facility
represents the state of the art in such a sky
simulator. Although the facility has been used
over the last few years on a limited basis by
practicing designers, it has been used primarily
as a research facility. However, the flexibility
and control built into the facility for research
purposes provides an ideal capability for the
designer who would like to accurately evaluate
daylighting performance of complex designs under
many sun and sky conditions in a short time
period. In the future, the facility will be made
available to designers having appropriate pro-
jects. Sample results from a recent atrium
research study are shown in Figure 2. The simula-
tor has also been used to help refine atrium
designs in several recent architectural projects.
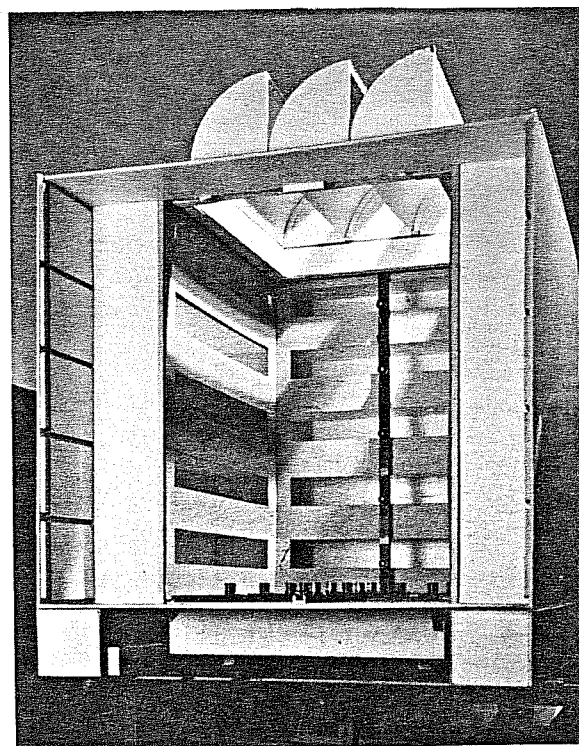

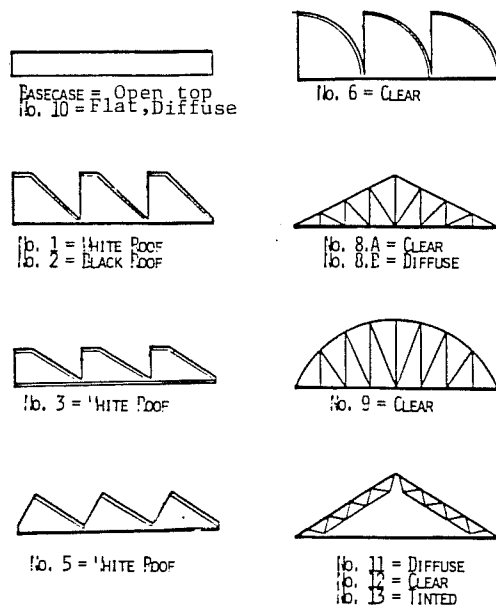Figure 2.A: Atrium model for testing.

Figure 2.B: Schematics of 8 of the 14 atrium roof
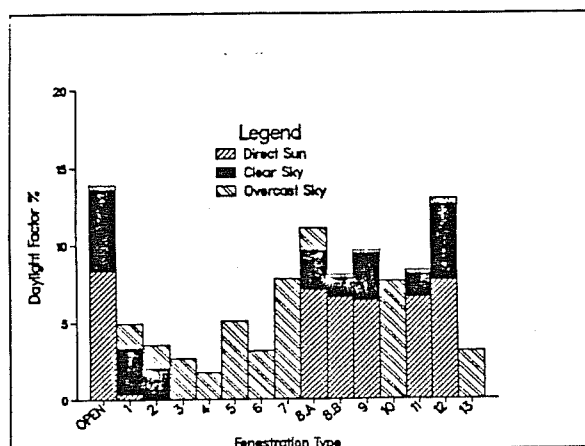tops tested.

Figure 2.C: Illuminance (daylight factor) at center of 9-story deep atrium floor for 14 skylight types under three sun/sky conditions.

Lighting Quality Assessment

In some cases our primary interest is the relative difference between the daylight transmittance properties of the major glazed element. With an atrium design, for example, the interior design variables may be fixed by other elements of the design program, but there may be some flexibility in specifying the roof glazing system. A comparative analysis of the light-transmitting ability of various roof glazing systems might provide the information needed to make the proper design decision. The researcher is interested in two primary optical properties of a glazing system. First, the total hemispherical transmittance is a measure of the total light transmitted, including both the directly transmitted component and the interreflected and transmitted component. A related quantity, the solar transmittance, is essential to determining the total solar heat gain and potential cooling load impacts. These transmittance properties may vary enormously with incident angle, but will tend to be independent of the building space behind the glazing system. It thus may be useful to measure the hemispherical transmittance of alternative glazing systems alone. A comparison of these measured properties may provide useful insights into the hourly and seasonal patterns of daylight and sunlight admittance.

The hemispherical transmittance of a glazing material or fenestration system can be calculated in some cases, but is more readily measured using a newly developed large integrating sphere, shown in Figure 3. This sphere can accommodate a sample of up to two square feet and is illuminated at any incidence angle by either direct sunlight outdoors or a collimated sun simulator indoors. Glazing materials samples can be tested, as can scale models of much larger fenestration systems such as an atrium roof or a curtain wall incorporating a

light shelf. In this case, not only is it important to measure the fenestration materials properly, but supporting structures such as roof trusses must be accurately modeled in scale if the optical results are to be representative of those obtained in a real building. These structural elements may serve as light-diffusers to prevent direct sunlight penetration into a space. The relative light losses associated with each diffusing system can be readily measured and compared. In this instance a new research facility designed to measure optical properties of a fenestration system could provide useful results to designers who understand the measurement process and the types of design insights that it can provide.
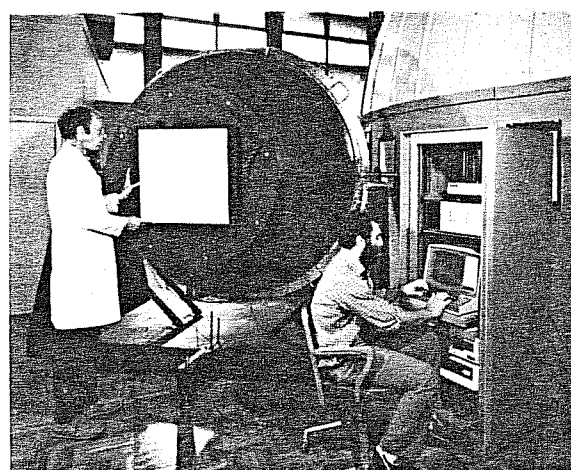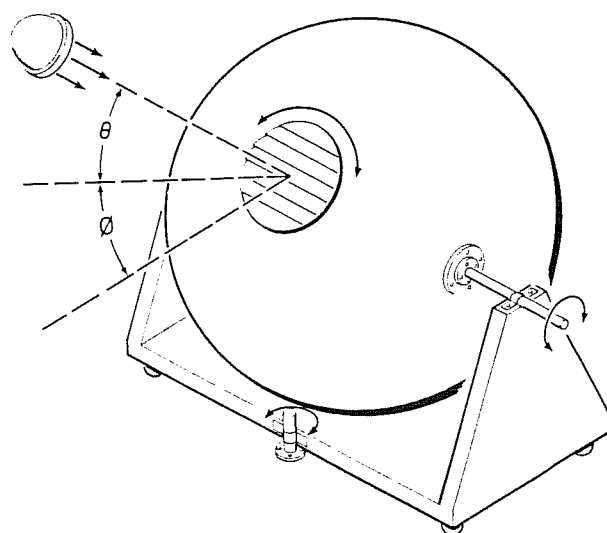

Figure 3.A: Photograph of integrating sphere for measuring hemispherical transmittance of glazing materials.

XBL 844-8410

Figure 3.B: Diagram of integrating sphere.

In addition to the total visible flux transmitted, one would often like to have information on the directional properties of the transmitted flux. The researcher is interested in the bidirectional transmittance of a fenestration system, which is the luminance viewed from each output direction of the fenestration system as a function of each input direction. These data are important not only to understand the quantitative illuminance distributions resulting from fenestration systems, but also to determine the potential glare contribution and other aspects of lighting quality. For simple optical systems these properties may be calculated, but for more complex and architecturally realistic systems they must be directly measured. We have recently developed a large luminance scanner to make these measurements for optical materials, shading systems, and complete fenestration systems or building elements reproduced in scale. The prototype of this system is shown in Figure 4.

Figure 4. Luminous scanner for measuring directional transmittance of glazing materials.

The data produced by the integrating sphere and the luminance scanner may at first seem remote from the experience of a building designer. However, the designer deals routinely with analogous quantities in electric lighting design. The total light output of most electric light sources is measured in an integrating sphere in much the same way that the total light transmitted by a fenestration system is measured by our device. In addition, the candlepower distribution of luminous flux emitted from an electric light fixture is also measured empirically by fixture manufacturers in much the same way as the light distribution entering a room from a fenestration system will be determined. Unlike the light fixture, which has a single candlepower distribution when fitted with a particular set of lamps, the light distribution of our "window fixture" results from the ground-reflected light, diffuse skylight, and direct sunlight at each incident angle. Furthermore, for operable devices such as venetian blinds or vertical louvers, each color or blind finish and each blind position may result in a different candlepower distribution for each incident sun condition. One sees immediately that the measurement and data-handling problems are severe. We are confident, however, that the data collected by this measurement system can be condensed and presented in simplified formats for intelligent evaluation by designers as well as being utilized in a more complete form as numerical data bases that can be accessed by computer models. This situation is entirely analogous to the use of photometric data bases in electric lighting design today.

The complexities of detailed photometric measurements should be apparent from the preceding discussion. Computer simulation models can be attractive because they avoid many of the difficulties of experimental work. However, as stated earlier, the readily available simplified models frequently are incapable of analyzing the more sophisticated designs that most interest the building designer. In fact, it has been said that most of the building cross sections that are simple enough to be analyzed by a typical microcomputer program are also simple enough to be understood without computational tools by the experienced designer. We developed a new main-frame computer model for daylighting simulation, SUPER-LITE, which is intended to provide a modeling capability for realistic architectural spaces and complex fenestration systems. Most daylighting models are limited to rectangular spaces and simple window design. SUPERLITE allows specification of more geometrically complex non-rectangular spaces, and as described in the next section, allows us to simulate the daylighting performance of complex fenestration systems. To model complex fenestration systems, we use the experimental data collected by the sphere and the scanner.

Rather than treating a glazed area in the room as a transparent or translucent surface through which a portion of the sky may be viewed directly from each interior point, we treat the glazing system as a window fixture whose construction and optical properties are unknown but whose net directional transmittance is completely specified by the bidirectional transmittance function as described earlier. These functions are drawn from a library of measured data rather than calculated within the program, thus greatly simplifying the computation while at the same time adding the power and flexibility to model virtually any fenestration design for which appropriate experimental data can be obtained. This hybrid approach--using a detailed illuminance model coupled to a measured data base--provides the versatility and power of a simulation model with the speed and flexibility that would be unobtainable if the program was required to directly calculate the complex optical properties. Furthermore, it allows us to determine the performance of novel architectural designs as long as a scale model can be constructed and measured in the illuminance scanning facility. For innovative designs that might use curved, semi-specular surfaces (e.g., brushed aluminum panel), this is the only approach that appears to provide some combined measure of accuracy, realism, and computational efficiency. A typical output from the SUPERLITE program, shown as an isolux contour on the work plane, is shown in Figure 5.

Sky is clear
Sun position: 65 off zenith
30 off S to E
Horizontal illumination
Direct sun: 2407 fc
Sky: 1298 fc

Contour Number	Illum. Level (Ft-candles)
1	20.0
2	40.0
3	60.0
4	80.0
5	100.0
6	150.0
7	200.0
8	250.0
9	300.0
10	400.0
11	500.0

Windows marked by •••••
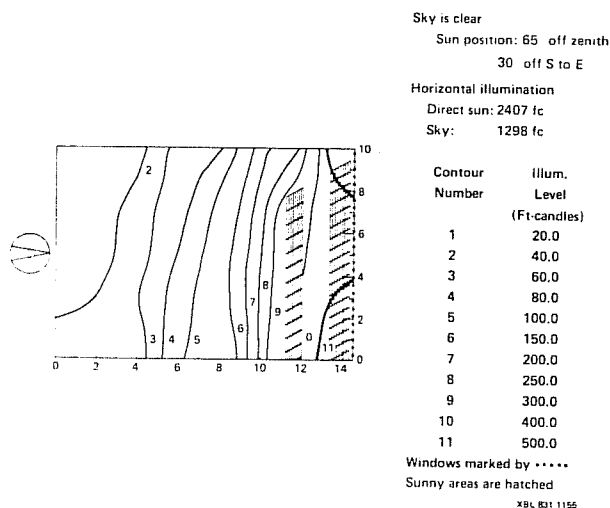Sunny areas are hatched
XBL 831 1156

Figure 5. Isolux contour showing daylight illuminance distribution as calculated by SUPERLITE.

The SUPERLITE model has also been adapted to calculate electric lighting distribution so that the combined integrated electric light/daylight system can be examined in detail in a space. Designers often view research tools as striving for ever-increasing accuracy. While improvements in accuracy may be desirable, the more significant capability of the SUPERLITE model is its versatility and ability to model illuminance distribution in complex (i.e., realistic) architectural spaces and to account for the influence of the high-performance fenestration systems that are gaining popularity in new buildings. In this instance, the interests of the architect and researcher are very similar, although perhaps for different reasons. However, this versatile simulation capability comes at a price; the cost and complexity of this computational tool are still be a stumbling block to widespread use in the design field. However, interactive graphic-based preprocessors and other interactive modeling techniques may some day eliminate this obstacle.

Energy Analysis Tools

An evaluation of lighting quality and quantity is an essential first step in determining the net annual performance in daylighted buildings. To better understand the energy-related impacts, an annual energy simulation model that properly accounts for daylighting effects must be utilized. Once again, there are, and will continue to be, a variety of simplified models that account for both daylighting and thermal effects in a building. However, most of these will account for only the simplest daylighting systems and may not properly account for the interactions among the occupant response to daylight in spaces, operable fenestration systems, sophisticated lighting control strategies, and window management. The DOE-2 program is widely used in the building research community and used to varying degrees by those in the public and private building design sectors. The DOE-2.1B version of the program incorporates an integrated daylighting analysis module. In developing this capability for the program, a major effort was invested to provide a variety of useful data to the user, both researcher and practitioner. In fact, many of the output reports that are of interest to us as researchers are also of great interest to the architectural designer. Some of these reports provide insights into the nature of daylighting performance in a building; others allow the user to extract information on the effect of alternative design variables without re-running the program.

The DOE-2.1B daylighting model incorporates window management routines that allow the user to specify the thermal and solar optical properties of shading and insulating systems and the environmental conditions under which they are employed.

Window shading systems can thus be controlled on the basis of a glare index calculation, on the basis of transmitted solar heat gain, and on the basis of a set hourly schedule. Automatic control can be simulated, or an "imperfect" occupant can be simulated for whom the proper operation is calculated but is carried out only for a user-specified fraction of the time. Although we do not yet have adequate models to predict how frequently and how carefully an office occupant will pull the shades to reduce glare and thermal discomfort, we can at least model the energy implications of several versions of this strategy to determine the probable impact on energy costs. This is the type of practical data that will interest many designers by helping to decide between fixed vs. operable shading and manual vs. automatic control.

The implementation of a daylight modeling capability in DOE-2 was planned with a view toward adding future enhancements with a minimum of changes in the overall program structure. Figure 6 snows a schematic plan for the daylighting and thermal calculations in new versions of DOE-2.

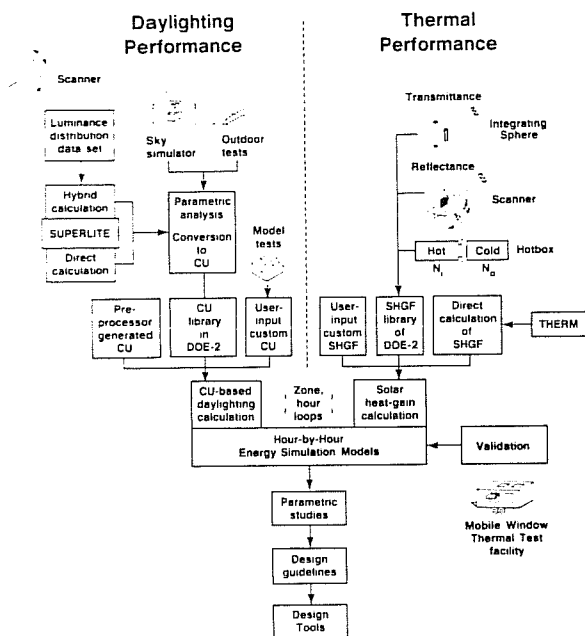**Daylighting Performance** | **Thermal Performance**

Figure 6. Schematic for incorporating advanced daylighting and thermal calculations into the DOE-2 computer program.

Figure 6 illustrates a parallel computational structure for both solar heat gain and daylighting, and indicates a number of alternative pathways depending upon whether simple solutions or more complex architectural designs are being studied. If one is attempting to optimize the day-

lighting and cooling load benefits, it is important to model each effect with approximately the same level of accuracy. Furthermore, it is these effects that drive peak cooling load, chiller and HVAC size, and peak electric demand. If these quantities are to be accurately estimated, it is important to have hour-by-hour models that are sensitive to variable exterior conditions, variable fenestration operation, and to the possible or probable window management strategy of building occupants. The schematic in Figure 6 defines the major tasks and objectives in a multi-year research program that is well underway. Although the schematic suggests that useful guidelines for building designers emerge from the use of the program, as we suggested previously each component calculation also provides useful data for the inquiring designer.

Accurate and economical calculations of annual energy performance are not the only important output of a large simulation program such as DOE-2. A significant investment went into developing a series of reports to provide different levels of information for the researcher and the engineer or architectural designer. In addition to the standard DOE-2 monthly energy and load reports, there is a new series of daylighting reports that provides several types of information. One set of reports gives the average monthly daylighting savings, average monthly footcandle levels, and glare index for each building zone. A second series of reports provides the average hourly/monthly savings for each zone. These can be scanned quickly to see patterns of daylight savings across days for particular times of the year, and across months for particular hours of the day. A third level of reporting detail is provided by a series of statistical summaries that indicates the percent of time that the daylight illuminance falls within certain limits for each month within each building zone.

These data are then summed and presented as the cumulative probability that each illuminance level is exceeded on a monthly basis for each zone. The reports enable the user to determine the effect of changing control strategy (for example, from multi-level switching to continuous dimming) or to determine the effect of a change in design illuminance level without re-running the DOE-2 program. Finally, there is the option in DOE-2 of examining the daylighting performance in any zone in the building in hourly detail for specific days. This is particularly useful for investigating the detailed operation of operable systems and occupant response systems for average design days or peak days. Most users of large complex program such as DOE-2, either designers or researchers, quickly develop techniques to scan and evaluate data in a variety of reports to better understand the component and overall building performance issue. It is important for both

the designer and the researcher to have the option of investigating daylighting patterns in more detail than are traditionally given by annual energy figures. Tools that provide this level of detail and these insights in readily accessible form will be preferable to those that do not.

Further analysis of the performance data from these types of simulations may reveal fundamental relationships that allow detailed analysis of related designs without the time and expense of a full-blown, hour-by-hour simulation. In fact, recent studies at LBL have suggested that the performance of daylighted buildings can be adequately described using a series of relatively simple equations and a statistical data base resulting from regression analysis of a large number of DOE-2 runs. These simplified performance expressions assist the researcher in understanding the relationships between the climate and occupancy variables, and the design conditions in the building. The same results provide a powerful assessment tool, enabling a designer in the early stages of design to quickly determine optimal glazing conditions or evaluate the positive or adverse effects of decisions that must be driven by non-energy factors. The ability to generate these numbers quickly makes it useful in early design stages. The fact that they are developed from detailed DOE-2 simulations provides confidence that, at least within the limits of the conditions simulated, the simplified results reproduce most of the accuracy of full-blown DOE-2 simulations that would require hours of work and hundreds of dollars of computer time. These same performance equations have the potential for being developed into a user-friendly microcomputer-based design tool with appropriate packaging and input/output graphics.

We note, therefore, that the basic experimental tools and algorithms provide the building blocks for researchers' development of new simulation models and provide data that are and could be made useful for practicing designers to better understand the daylighting performance of fenestration systems. The energy analysis simulation models are also structured in a variety of ways to provide different levels of details for investigations by researchers or practicing designers. Finally, the hour-by-hour analysis models can be used to develop simplified performance expressions, which in turn become the basis for simplified design tools. Throughout this process we see potentially strong interrelationships between the interests of researchers and designers.

Future Research Directions

In the future, daylighting design tools will increase in sophistication and power. It is clear that simulation-based tools will advance most rapidly, given the accelerating trends in hardware and software in the computer field. Using the hybrid experimental/computational techniques described earlier and data bases accumulated from extensive model testing, we believe it will be possible to accurately simulate the illuminance and energy performance of a variety of complex building designs and fenestration systems. Improved input/output graphics will facilitate a designer's use of these tools. These tools also contain the potential for a quantum leap in improving the designer's understanding of visual comfort and visual performance in a luminous environment. Many computer models calculate room surface luminance distributions as part of the workplane illuminance calculation. Trends in lighting designs suggest that it is important to provide luminance maps of both daylighted and electrically lighted environments. Improved three-dimensional modeling capabilities and computer graphics to provide shading make it possible to show light distributions on the surfaces of building spaces. It is a conceptually simple, but computationally complex, extension to include luminance maps of room furnishings and other features in occupied spaces. Such systems have been available to researchers for a number of years, but are only beginning to be available to designers. Until recently, these tools were based on complex computational models, which limited their applicability to those with access to large computer systems and large budgets.

The research directions described in this paper, in which we combine measured experimental data on the daylighting properties of fenestration systems with basic computational models, should allow us to generate the technical basis for luminous maps of interior environments or "synthetic photographs" having the realism now obtainable only through much more complex and costly simulations. These types of modeling capabilities in the hands of an experienced designer could allow alternative environments to be visualized by designers and clients well before costly commitments to the building structure and interior furnishings are made. To make the various tradeoffs involved in optimizing both the daylighting and thermal aspects of fenestration design consistent with other elements in the building, the system we are describing needs to draw on a variety of illuminance and energy data bases based on prior computational results as well as measurements. These will be based on use of luminance mapping in real environments, luminance mapping in scale models, sky simulator measurements, SUPERLITE

simulations, and measured photometric properties of fenestration systems. This illuminance data base would be complemented with a variety of component and total energy results derived from DOE-2 simulations. Finally, these multiple data bases would be linked with an "expert system" that allows the elements of the data base to be manipulated in an appropriate way based on the design requirements of each building. This will require that we integrate state-of-the-art technical data from the research community with the expertise of skilled designers whose concerns, perspectives, and insights can be captured and organized into a system format to move the entire process. During the next few years, the development of such an expert system for fenestration design in buildings will be a major objective of our research program. The success of such an endeavor should reduce the cost and risk for design professionals who wish to create more pleasing, productive, and energy-efficient environments in buildings.

For a bibliography listing papers and design tools developed by the Windows and Daylighting Group at LBL, please write to the author at:

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